A Fresh Look at Energy, Materials, and Labor in Agriculture

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An understanding of agriculture's energy, material, and labor requirements is essential for achieving economic and ecological sustainability, and for assessing the effectiveness of relevant policy decisions (biofuel subsidies, regulations, labeling, etc.). Previous studies of energy, materials, and labor use in farming have been based on either unverified voluntary reporting[9–11] or test plots,[8] rather than on the high-resolution measurements of mass and energy flows.[17] Here we present a recursive analysis of 1.25 million data points describing in unprecedented detail the resource transactions on a 60 ha farm functioning for over 6 years. This analysis highlights the importance of accounting for all types of materials, as well as capital equipment, non-field labor, and commuting. The superior energy efficiency of the farm's energy-saving methods, including green manure, crop rotation, composting, and short-duration grazing – compared with conventional methods – persists even when the higher labor requirements are taken into account. One of the farm's methods, however – the use of horses for traction – is shown to be highly inefficient compared with mechanical tractors.

KEY WORDS: chemicals-free — draft horse — tractor — photovoltaics — livestock — organic —crop—rotation

Introduction

Conventional chemical-based agricultural methods achieve much higher yields than traditional approaches, but at high ecological and energy costs.[1–5] Modern organic production methods may provide improved sustainability,[6,7] but attempts to assess the energy and labor trade-offs of moving from conventional to organic methods have been either based on test plots,[8] which do not capture the full workings of a complete farm, or on unverified voluntary reporting.[9–11] Besides the questionable accuracy of such data, they also fail to account for the whole range of materials consumed in farming, such as farm equipment, buildings, and sundry materials;[8,12,13] they also do not take into account worker commute and food transportation energy. The weakness of the existing farming energy and labor data also calls into question all previous work estimating the energy balance of crop-based biofuels[9–11] – a critical issue, as the use of such biofuels is increasingly widespread and now mandated.

Here we present a study of a 60 ha farm in the midwestern U.S. where every action involving energy, materials, or labor was recorded in detail in a database over a 6-year period (1992-97). The comprehensiveness of the resulting database is unprecedented, and offers a picture of the requirements of farming that is both more detailed and more accurate than ever before. The database has made it possible to isolate the individual components and efficiencies of the farm, so that these can be compared directly to the full range of previous studies. Although the study farm was organic and employed methods intended to improve its sustainability, the results also make it possible to assess the importance of such detailed accounting.

The Study Farm

The study farm had 20 ha of cropland and 40 ha of pasture. Crops were primarily a 5-year rotation of intermixed strips of grain sorghum (*Sorghum vulgare*), soybeans (*Glycine max*), oats (*Avena sativa*), sunflowers (*Helicanthus annuus*), and soybean cover employed as a green manure. Alfalfa and sweet sorghum (*Sorghum saccharum*) were also grown for animal feed. Tillage was by conventional plowing and disking methods, with no irrigation employed.

Animals on the farm included flocks of approximately 50 egg-laying hens and 75 broilers, as well as two draft horses and 9 to 28 cow-calf pairs (Texas Longhorns) on the pasture.

All transactions on the farm involving energy or materials were individually measured and recorded, with the exception of regularly repeated tasks, which were recorded weekly. Each record included the date, object (i.e. purpose of task), task type, transaction type, power source and instruments used, managerial and other labor hours, materials and animals involved, durable item lifetime, and the portions of the farm affected, resulting in a database with 1.25 million entries.

The farm employed several techniques for reducing energy use. No chemicals were employed on the farm, avoiding a major consumption of embodied energy. Forty percent of the crops grown were nitrogen-fixing legumes. One-fourth were green manure and three-fourths were forage and soybeans. These proportions were chosen to balance the farm's nitrogen and phosphorus inputs and outputs. The only external fertilizer inputs were in purchased feed. They amounted to only a few kg of elemental nutrients per ha annually in manure on the pasture and cropland.

The poultry were raised free-range and in a portable pen, and short-duration grazing management of the cattle was employed to maximize productivity and sustainability while keeping inputs low. Beef yearlings also grazed directly on crop strips.

Average crop yields for the study farm's major export crops, soybeans (30 bu/acre) and milo (53 bu/acre), were somewhat higher than those of the local (Saline county) conventional farms (25 and 49 bu/acre respectively);[14] yields for the other two top crops were lower – 38 versus 47 bu/acre for oats, and 2.6 versus 3.2 tons/acre for alfalfa. Yields for other crops were also a mix of higher and lower compared to the local baseline, and generally within one standard deviation of the local yield distribution.

The farm included a small (4.5 kW) photovoltaic array. Due to substantial construction associated with the array, including a battery bank and grid tie, the energy inputs to the system were roughly equivalent to the projected 20-year output of the array. The inputs and outputs of the array in the farm database were easily separable from the rest of the farm, so that the existence and operation of the array make no difference to any of the other energy ratios reported.

The soil chemistry of the farm, including NPK, pH, CEC, and organic matter content, was measured before and throughout the project. Although some nutrient levels fell as production began, the data indicate the long-term stability of soil fertility, and thus the sustainability of the farm's methods. The statistics were not strong enough, however, to clearly demonstrate superiority to conventional farming, as has been done in other studies.[3,8]

As the traction available to the farm exceeded its needs in both number and size,[15], the capital costs associated with the tractors was adjusted to reflect the requirements of a farm of similar size, with significant margin.[17] Maintenance and fuel costs, though presumably higher than would have been incurred by an appropriately-size tractor fleet, were not adjusted.

Methods

Energy Flows. To deal with the complex relationships between the many parts of the farm – and thus obtain the energy and labor efficiencies necessary for direct comparisons with previous studies – the matrix methods of economic input-output analysis[16] were adapted for this study, using the MATLAB programming language. In the database, the farm was divided into 70 components called objects – each representing a well-defined part of the farm's activity, including animal types, crop species, power sources, vehicles, and tools. Each entry into the farm's database included a specification of the object to which the activity was devoted, e.g. plowing for a crop, building a shed, watering horses, etc. To calculate the ultimate assignment of energy inputs to exports from the farm, inputs to objects – consisting of combinations of direct fuel and electrical energy, material embodied energy, and labor hours – were assigned to other objects and exports as shown in Table 1. For example, energy expended on care of the horses was distributed to the crops in proportion to the acres worked by the horses. To assign each input ultimately to exports, inputs attributed to objects by application of these rules were re-distributed using the same rules repeatedly, until all inputs were ultimately assigned to exports. This iterative approach captures accurately the recursive nature of the relationships between the farm components, e.g. seed inputs to crops feeding horses plowing crops, and has been described in greater detail elsewhere.[17]

The proportions of the total inputs to the farm, excluding labor but including embodied energy in fuel, electricity, feed, seed, animal, capital equipment depreciation, and supplies (all other materials) are shown in Figure 1. Capital equipment depreciation (including vehicles, structures, and tools) amounted to 7.7% of all inputs; this input is uncounted or only partially counted in all previous studies. The "supplies" category, encompassing a wide range of materials, accounts for considerably more energy inputs that have not been accounted for in any previous study.

Horses Versus Tractors. As the farm employed both horses and motorized tractors, the data make it possible to compare their energy and labor efficiencies. The inputs to each traction source consisted of capital depreciation, fuel, and maintenance costs. Though horses do not use fuel, their maintenance requirements (including feed) were far higher than those of the mechanical tractors, so that the horses' total energy expenditure per worked acre was 6.4x and 7.8x higher than the two main tractors of the farm. This excludes labor but includes all energy going into the growth of the crops used to feed the horses. The horses were clearly underutilized, however, as they were employed only an average of 2.36 hours per week, and worked only 6.4% of the farm on an acreage basis. Since inputs to the horses are only weakly dependent on hours worked, higher horse energy efficiencies seem possible with greater utilization. However, labor efficiency for the horses was extremely low – 492x and 187x more labor per acre than the tractors, including handling and growing their feed.

The high level of detail of the farm database made it possible to estimate the efficiency of the farm's various production techniques with and without the horses. To obtain the farm's efficiencies in the no-horse scenario, all inputs of labor, fuel, supplies, and feed to the horses were eliminated, as well as all horse-related capital equipment, and acres worked by horse power were assumed to have been worked by a use-weighted average of the other traction sources. Crops grown to feed the horses were assumed to never have been planted.

Comparison with Previous Studies. Figure 2 shows the energy inputs to each of the farm's major crop exports by category, compared with previous studies, for both the horse and no-horse scenarios. For consistency, the quoted quantities of materials were multiplied by uniform embodied energy factors to obtain energy values, rather than directly using the energy values quoted in other studies that were based on varying embodied energy factors. Fertilizer and chemical inputs for the study farm were counted as zero, as all inputs related to crop fertility are reflected in the fuel, capital, and supply categories. None of the previous studies took into account the full range of inputs to farming; only fuel, chemicals (including fertilizer), seeds, and in some cases capital equipment were included. This difference is shown in the "Supplies" portion of the energy inputs shown, and it amounts to 15-27% of the total inputs. The Pimentel studies do not take farm buildings into account. Sheehan does not take capital equipment into account at all; capital depreciation accounts for 7.7% of non-labor inputs to the study farm.

Figure 3 compares the energy efficiency of the animal production systems of the farm. Animal export calories required 14-34x more energy input than export crop calories. Beef production is considerably more efficient due to the cattle being mainly grass-fed. The "supplies" category, unaccounted for in previous studies, amounts to 34% of the beef production energy input.

There have been few previous studies of the energy efficiency of animal production. An interpolation of Heitschmidt's calf and yearling results[18] to match the study farm's method most closely obtains an energy ratio of 3.17:1, almost half that of the study farm, 5.95:1. This difference may be due to the much larger herds in Heitschmidt's work (250-1000+ head), and to the more complete accounting of the study farm.

Comparison to Pimentel's protein production energy ratios (based on USDA data)[19] obtains distinctly different results. The study farm's protein production efficiency is almost twice that of feedlot beef, and is essentially equal to Pimentel's ratio for grass-fed beef. Egg production on the farm was almost twice as efficient as conventional battery cage methods, but the chicken meat ("broiler") production was 4.7x less efficient than conventional battery cage production. Broilers were fed imported, high-embodied energy feed almost exclusively, and represented less than 0.5% of the farm's outputs.

Labor Energy. The study farm's organic production system used less total energy than conventional systems but used more labor. To assess this trade-off it is necessary to assign an energy cost to labor. Following Costanza, Herendeen, and Fluck[20–23] we estimate a value of 75MJ/hr for rural labor in the United States; this value is similar to that found by previous studies[24–26] using other methods. Figure 4 shows the energy ratios of the study farm and previous studies including labor at this rate. For direct comparison to the previous studies, the study farm labor includes only field operations such as field preparation, hauling, and other directly crop-related activities, including the labor to grow green manure crops.

A full accounting of the study including all labor noted in the farm database, including horse husbandry, transportation, repair and maintenance of equipment, construction, farm management and planning, etc., has been presented elsewhere[17]. Including this non-field labor increases the labor total by 35-55% for the major crops of the farm. Most of the laborers on the study farm were short-term volunteers; with more experienced workers, labor hours might be significantly reduced.

Commuting Energy. The hour-by-hour picture of the farm's activities in the database makes it possible to estimate the number of commuting trips necessary to run the farm. None of the farm workers lived on the farm or within walking distance. The lowest possible number of commutes possible to perform the work on the farm was estimated for manager and non-manager labor, the two categories of worker specified in the database, by assuming one commute for each category when any number of hours were logged in a day in that category. Using the per-trip commute energy assumed by Hill[10] and Patzek[13], this lower limit of commuting energy amounted to 34-54% of the 75 MJ/hr labor energy, and 16-46% of the total non-labor inputs.

Final Remarks

Our analysis of the unprecedentedly detailed energy flow database indicates that organic farming techniques can provide energy efficiency superior to conventional, chemical-based methods in most cases, although labor intensity is increased. This advantage persists even when the energy intensity of labor is taken into account. Using the organic methods of the study farm with the efficient multi-row equipment employed in larger-scale commercial agriculture would result in even more energy savings, and a sharper advantage for the organic methods.

Previous studies have failed to take into account capital equipment; a significant oversight. Further, taking into account the full range of miscellaneous materials employed in agriculture reveals an even larger energy input overlooked by previous studies. The data also suggest that previous studies significantly undercounted worker commute energy that might represent a large portion of the farm's inputs, comparable to traction and fertilizer. Taking the full range of energy inputs to farming into account could overwhelm the putative greenhouse gas or energy advantages claimed for many crop-based biofuels.

Acknowledgements Dr. Aaron Baum was partially supported through a grant from the Land Institute. The study farm work, data collection and analysis were supported through private donations to the Land Institute and volunteer work.

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Figure 1 All inputs to the Sunshine Farm by total embodied energy, excluding labor. Total is 1602 GJ over 6 years.

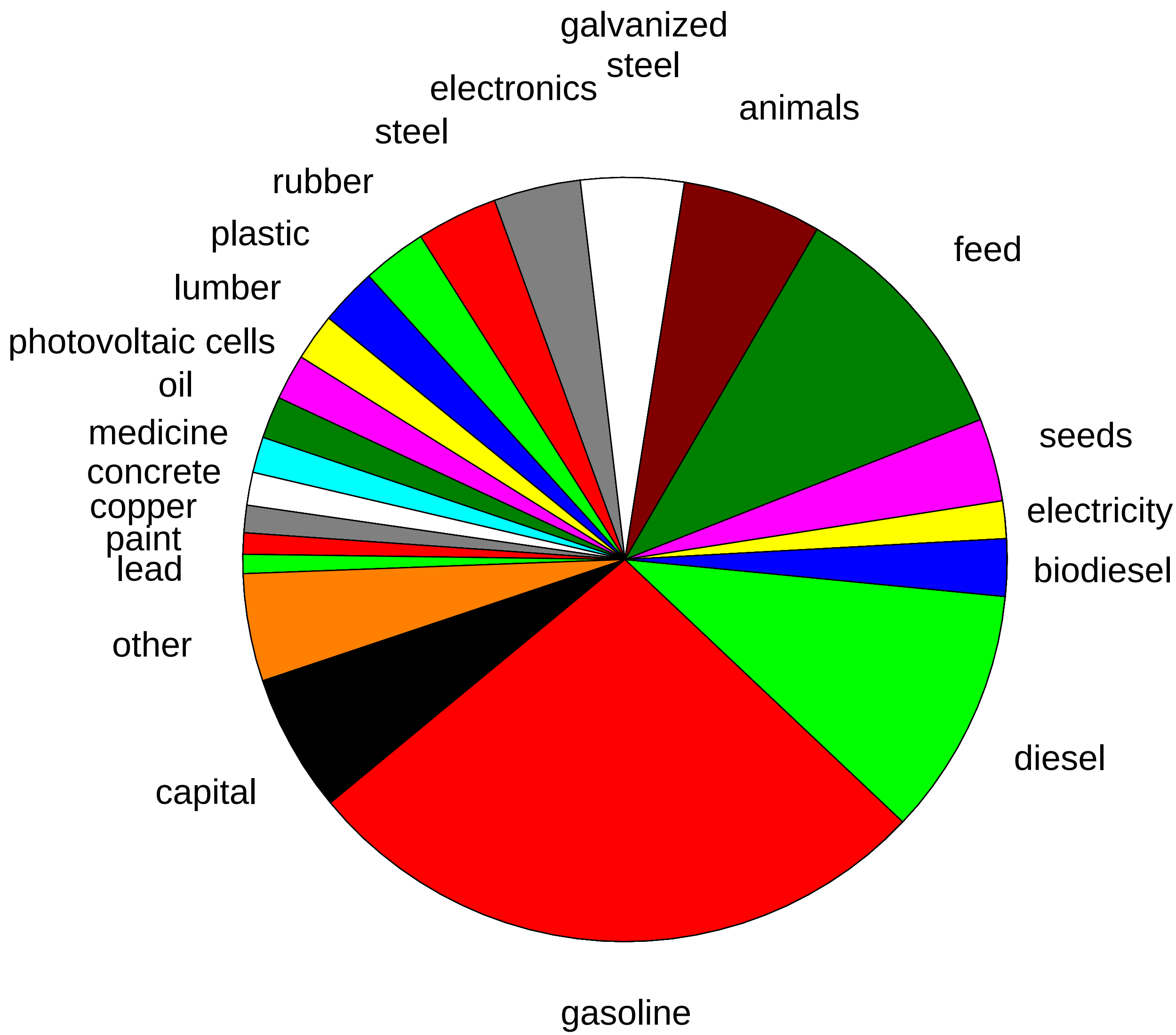
Figure 2 Energy efficiency of SSF compared to previous studies of conventional agriculture

Figure 3 Energy efficiency of SSF animal production

Figure 4 Comparison to previous studies including field labor charged at 75 MJ/hr

Table 1: How energy and labor inputs to farm elements (objects) were assigned to exports and other farm elements (objects) to build the Input-Output Matrix

Type of Object	Method for Assigning to Exports and Other Objects
Animal export	To corresponding animal export
Animal-related tools	Split among animals by entry fuel use
Feed and export crop	To animals and crop export by weights fed and exported
Electrical export	To electrical export
Feed	To animals by weight fed
Field power source or field tool	To crops by acreage treated
Non-field power source	To objects based on fuel usage
Forage	To animals by average animal mass during season
Green manure	To crops grown next season in same strips
Compost and general field prep	Split among all crops by planted acreage
Infrastructure	Uniform surcharge to all inputs
Farm management and planning	Uniform surcharge to all inputs
Outside services	To object, pro-rate maintenance and materials


galvanized
steel
animals
electronics
steel
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feed
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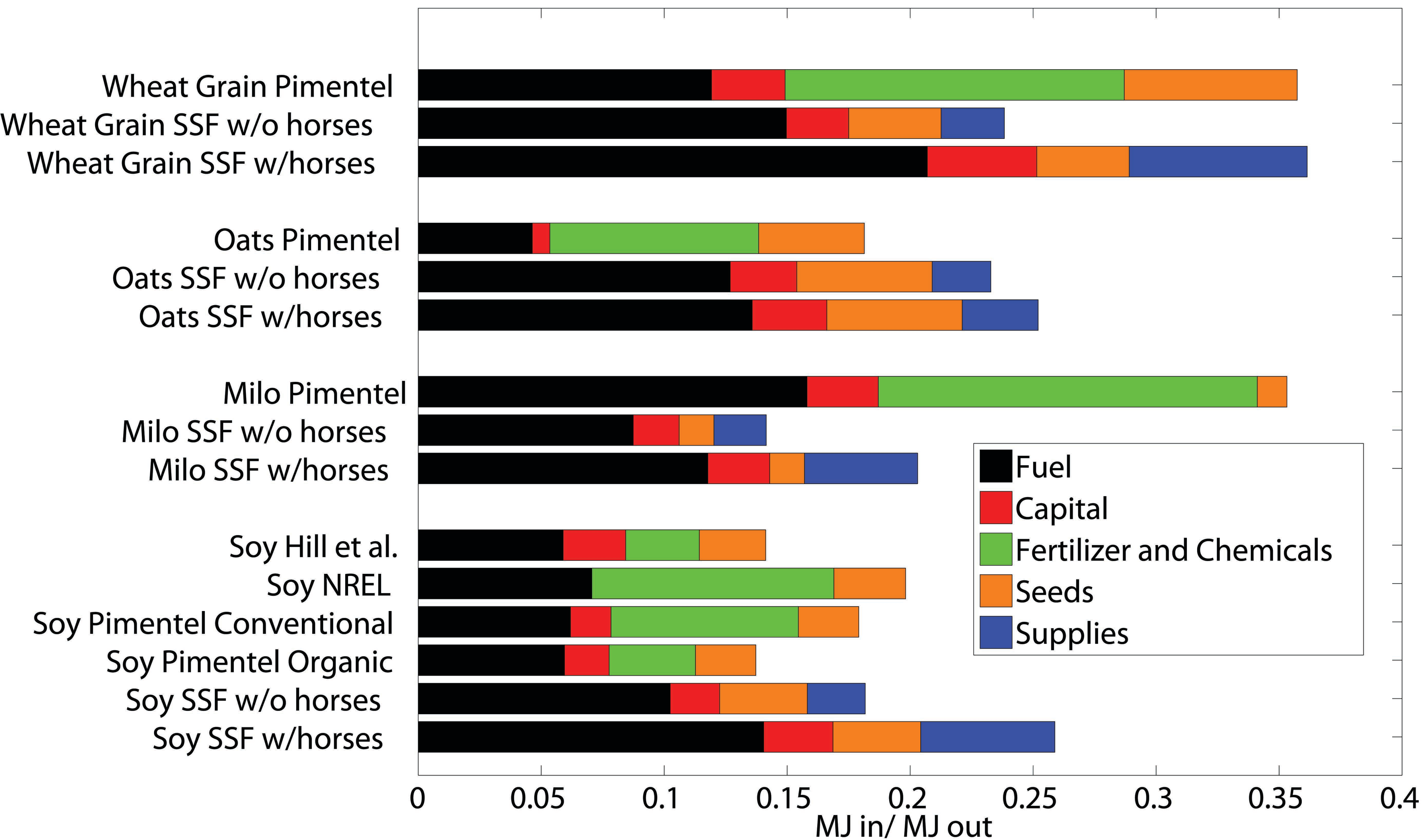
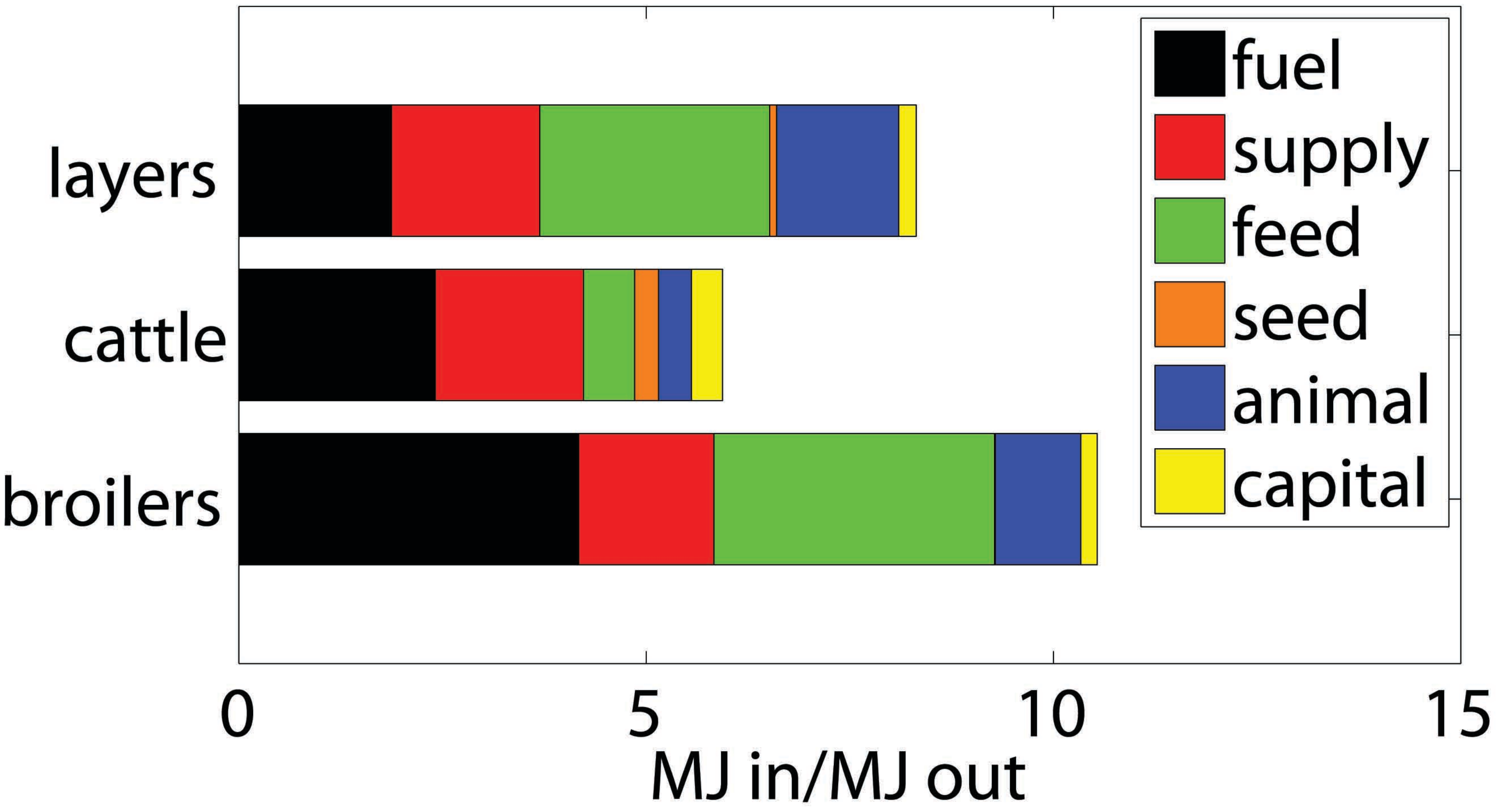
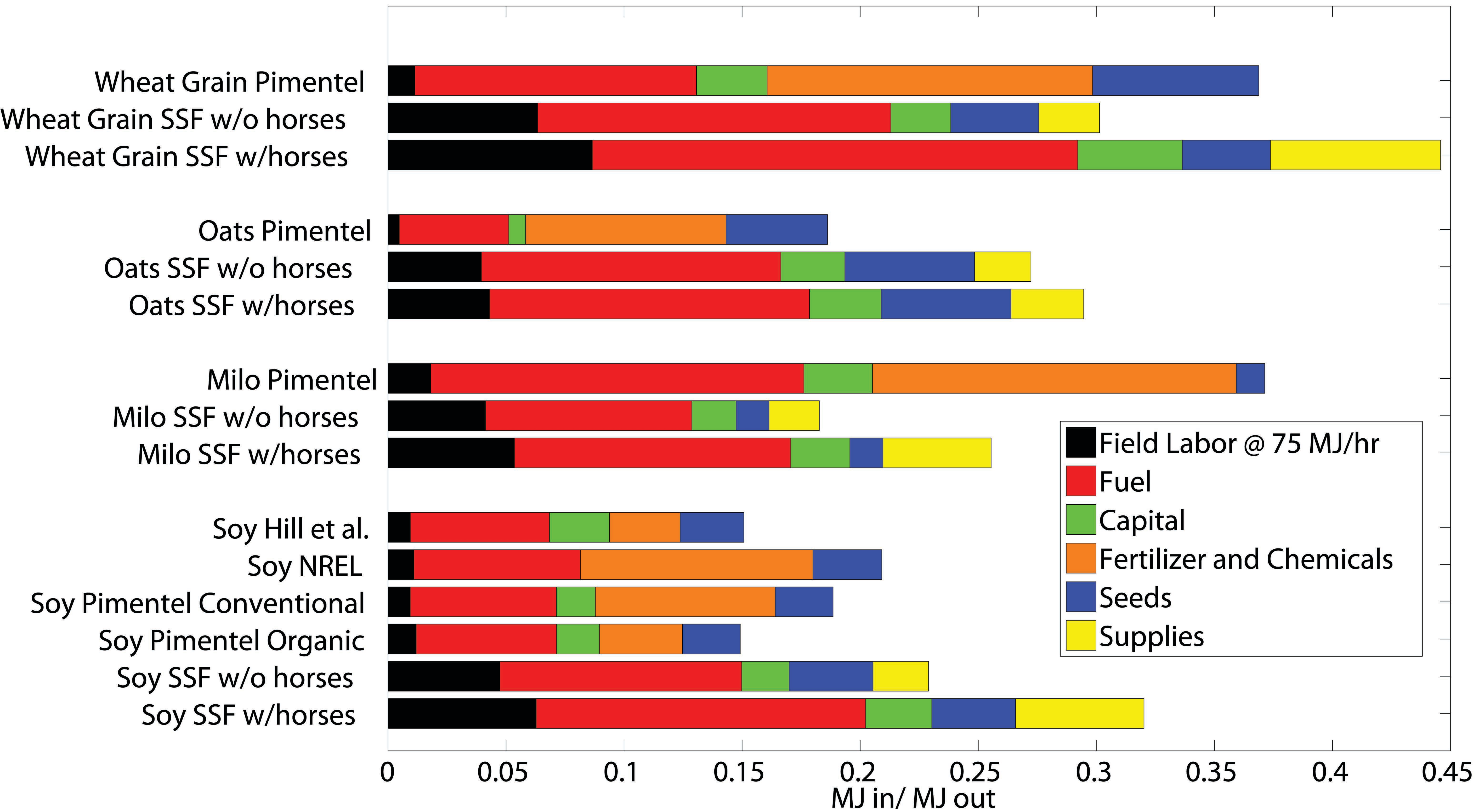
diesel
capital
gasoline



Wheat Grain Pimentel
Wheat Grain SSF w/o horses
Wheat Grain SSF w/horses
Oats Pimentel
Oats SSF w/o horses
Oats SSF w/horses
Milo Pimentel
Milo SSF w/o horses
Milo SSF w/horses
Soy Hill et al.
Soy NREL
Soy Pimentel Conventional
Soy Pimentel Organic
Soy SSF w/o horses
Soy SSF w/horses
Fuel
Capital
Fertilizer and Chemicals
Seeds
Supplies
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
MJ in/ MJ out



fuel
supply
feed
seed
animal
capital
layers
cattle
broilers
0
5
10
15
MJ in/MJ out


Wheat Grain Pimentel
Wheat Grain SSF w/o horses
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Oats Pimentel
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Milo Pimentel
Milo SSF w/o horses
Milo SSF w/horses
Soy Hill et al.
Soy NREL
Soy Pimentel Conventional
Soy Pimentel Organic
Soy SSF w/o horses
Soy SSF w/horses
Field Labor @ 75 MJ/hr
Fuel
Capital
Fertilizer and Chemicals
Seeds
Supplies
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
MJ in/ MJ out